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An Integrated Experimental-Computational Investigation of Connected Spaces as Natural Ventilation Typologies

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Abstract

This paper investigates the impact of spatial composition on the effectiveness of passive cooling by natural ventilation in a comparative study of the conical roofed Harran houses in Turkey and a passive solar home in the Midwest of the United States. While the projects are distinct and are situated in two extreme climate zones (hot and arid and continental humid) both projects have in common open variable configurations of multiple interconnected spaces. Computational fluid dynamics (CFD) simulations using OpenFoam were used to investigate the fundamental airflow characteristics and the resulting interior temperature and velocity profiles. The simulations were initialized as well as validated with measured field data. Subsequently, we tested the impact of the interconnected spatial composition of the buildings on their cooling potentials. This was accomplished by simulating variations of the spatial connections with reduced flow path connectivity compared to the original validated cases. Preliminary results regarding changes in temperature and air velocity show higher temperatures and lower velocities in the less connected cell-like spaces and indicate the importance of spatial connectivity for effective cooling by natural ventilation based on variable interaction of vents and flow path.

Keywords

Natural ventilation, computational fluid dynamics, spatial composition, climate design, vernacular building types

Disciplines

Acoustics, Dynamics, and Controls | Architectural Engineering | Architectural Technology | Architecture | Construction Engineering | Energy Systems | Environmental Design | Heat Transfer, Combustion

Comments

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An Integrated Experimental-Computational Investigation of Connected Spaces as Natural Ventilation Typologies

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ABSTRACT
This paper investigates the impact of spatial composition on the effectiveness of passive cooling by natural ventilation in a comparative study of the conical roofed Harran houses in Turkey and a passive solar home in the Midwest of the United States. While the projects are distinct and are situated in two extreme climate zones (hot and arid and continental humid) both projects have in common open variable configurations of multiple interconnected spaces. Computational fluid dynamics (CFD) simulations using OpenFoam were used to investigate the fundamental airflow characteristics and the resulting interior temperature and velocity profiles. The simulations were initialized as well as validated with measured field data. Subsequently, we tested the impact of the interconnected spatial composition of the buildings on their cooling potentials. This was accomplished by simulating variations of the spatial connections with reduced flow path connectivity compared to the original validated cases. Preliminary results regarding changes in temperature and air velocity show higher temperatures and lower velocities in the less connected cell-like spaces and indicate the importance of spatial connectivity for effective cooling by natural ventilation based on variable interaction of vents and flow path.

Author Keywords
Natural ventilation; computational fluid dynamics, spatial composition; climate design, vernacular building types .

ACM Classification Keywords
I.6.1 SIMULATION AND MODELING; I.6.4 Model Validation and Analysis

1 INTRODUCTION
Natural ventilation strategies use the building fabric and composition of vents and flow path to mediate the outdoor climate. These free cooling strategies will be essential to meeting the cooling needs of a warming planet. Spatial composition and building design can have a transformative impact on cooling potential for extreme climates as encountered in vernacular building types in the hot and arid Middle East as well as the continental humid climate of the US Midwest. Our overarching research goal is to enhance the utilization of naturally occurring energy flow through, within, and around buildings through the ordering of spatial composition as a means for reducing thermal energy consumption while retaining appropriate parameters for thermal comfort. The long-term research objective is thus the development of a knowledge base for passive ventilation strategies using CFD simulations validated by measurements for potential integration into contemporary sustainable high- performance building design. For the pilot project presented here, spatially enhanced natural ventilation strategies were simulated for two inherited building types using validated measured thermal air and surface temperature, as well as local weather data. The two building types are the Harran Houses in Southern Turkey and the Midwestern bungalow with its shaded porches. They have in common locations with extreme climates: the American Midwest and southeast Anatolia in Turkey and provide intricate spatial responses to the challenges provided by these climates. Clues for appropriate design strategies are embedded within many historical building types. These two typologies use a combination of buoyancy and wind driven ventilation strategies and a flow path across interconnected spaces.

This project is part of an architectural research endeavor to reveal the importance of architectural space for sustainable design and thus to reduce costly technical equipment to an effective minimum without compromising comfort. Our research team monitors the energy performance of a passive solar house and compares measured data with design predictions based upon whole building energy and CFD models. These analyses provide beneficial insights into spatial composition for new construction, building operation strategies, and their controls.

Considering air movement in natural ventilation is one of the most complex problems in developing passive design strategies, and design methods have yet to be fully computationally validated at the building scale as multiple previous publications have noted [Stoakes et al 2011a, 2011b, Passe 2007, 2008]. We hypothesized, that a significant key would lie in the space composition and materials of historical structures built in extreme climates utilizing locally available materials [Deza et al, 2015]. This work presents the preliminary results of this endeavor.

SimAUD 2016 May 16-18 London, UK

2 CASE 1: THE INTERLOCK HOUSE

Iowa State University's Interlock House was built in 2009 for the US Department of Energy's Solar Decathlon and has been installed in Iowa as a community laboratory for energy efficiency research (Figure 1 and 2). The house dimensions are approximately 11.8 m x 5.3 m with an inclined ceiling that rises with a 23 degree slope from 2.5 m to 4.7 m. The overarching goal of this project is to research the interaction of passive and active design strategies, and to develop sensible and delightful home prototypes for this challenging climate. The house provides one example of how net-zero energy living can be affordable today. It has been occupied in the Iowa landscape for the past four years while researchers study its energy base line and comfort parameters. By transforming to accommodate the extremes of the Iowa seasons and interlocking with the outdoors, this house balances a reduction of energy consumption through spatial composition and a tight, efficient envelope, with thermal and electrical solar power production.

Figure 1: Case 1: The Iowa State University Interlock House 2009 at the US DOE Solar Decathlon on the National Mall in Washington DC (Photo by Jim Tetro).

The spatial composition of the Interlock House can be seasonally adapted by reconfiguring the Hall and Sun Porch. The Sun Porch, with added thermal mass in the floor, mediates light and heat and encourages convective loops to heat and cool the house. A louver system spanning the south façade also mediates light and heat and reduces the active cooling load in summer months. The louvers allow occupants to manipulate light and heat according to activities and privacy needs. The house requires active manipulation of its doors, windows, and exterior louvers to influence airflow and to maximize or minimize heat gain and loss. This reliance on several basic passive solar and ventilation techniques reduces the energy demands for the active systems [Passe 2012].

Spatial continuity is achieved in section and plan by careful volumetric composition of six proportional modules. On the south side, the Sun Porch can be opened and closed to suit the seasons and become a sunspace in winter, a shaded porch in summer or be fully opened for a breezeway in the interim seasons. High clerestory windows on the north façade are spatially connected to the southern spaces across the auxiliary rooms for natural ventilation. [Passe 2011].

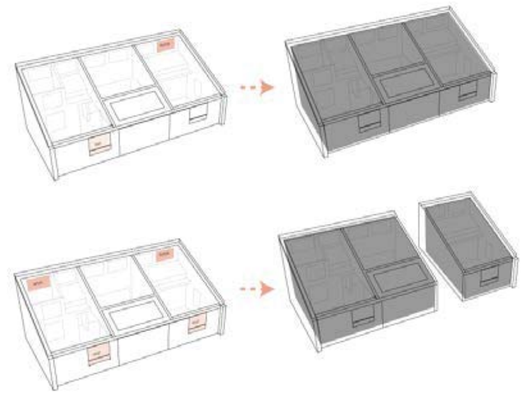

Figure 2: Case 1: Interlock House axonometric showing the interlocking spatial composition on top (Case 1A); the separation for the alternate cellular modelled case 2B.1 and 2B.2 bottom.

Figure 3: Case 2: Harran House view from the courtyard highlighting the composition of the connected corbelled domes.

3 CASE 2: THE HARRAN HOUSES

The corbelled domes of the Harran Houses (Figure 3 and 4) are a historic building type in the southern Anatolian region of Sanliurfa, Turkey, the base is built of large natural stones, plastered with adobe and the dome is built of mudbricks and outside adobe plaster. They are known by locals for comfortable cool temperatures in the very hot arid summers. Conversely, the interior spaces remain fairly warm in winter, when the outdoor conditions are cool. The key reason for the balanced performance of the Harran House is its sectional shape and construction materials as several authors have noted [Basaran et al 2011, Gomez-Munoza et al 2003, Faghih 2009]. Mutti [2014] has revealed that their strategically placed ventilation holes on walls and roof, and the connectedness of the corbelled spaces play a strong role in this condition while he reports measured interior temperatures of 29°C with outside conditions at about 42°C.

Preliminary measured and simulated data by Mutti (2014) was the basis for this research project. The overall project [Passe et al 2014] validates spatial typologies of these traditionally inherited passive heating and cooling strategies with computational fluid mechanics (CFD) models.

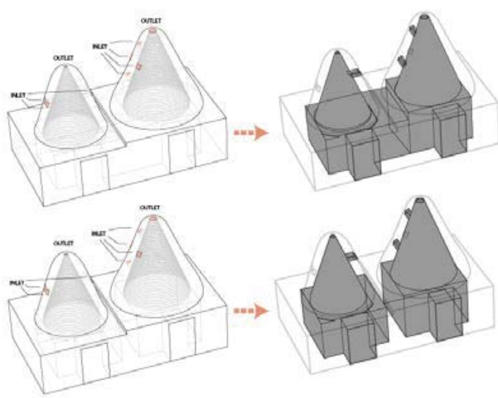

Figure 4: Case 2: Harran house axonometric showing the interlocking spatial composition on top (Case 2A); the separation for the alternate cellular modelled case 2B.1 and 2B.2 bottom.

4 METHODOLOGY

The overall Computational Fluid Dynamics (CFD) models have been validated with measured performance data taken from the Interlock House using approximately 50 air sensors and 60 surface temperature sensors (thermistors) [Deza et al, 2015] (Figure 5). Outdoor temperature and radiation conditions were also recorded. In addition, a collaborative pilot project studied the fundamental energy flow characteristics observed in the conical roofed Harran houses (Figure 3 and 4) in Turkey [Mutti 2014]. The surface and air temperatures were recorded in the Harran House, and compared with the aforementioned simulations.

Once the observations of these case studies were complete, our team modelled heat transfer and air movement within the Interlock House and the Harran Houses for summer conditions to understand what makes them effective spatial typologies for natural ventilation cooling. In both cases, we first simulated and validated the measured interconnected spaces with the complex interaction of spatial compositions, material properties, solar radiation and natural ventilation as a function of passive cooling. Then we used the same validated model to simulate the spaces without their connections and 'closed off' the opening between the rooms to shorten the flow path. The following sections describe the simulation parameters used and results obtained.

5 CFD ANALYSIS AND SIMULATION BACKGROUND

Computational Fluid Dynamics (CFD) was used to model the impact of spatial geometry on the flow pattern and distribution of air. For both the Interlock House and the Harran Houses a buoyant heat transfer numerical model with shear-stress transport (SST) k- omega turbulence model was used within OpenFoam to predict the combined cross- and stack natural ventilation flow using a 3D model of both house geometries and interior composition. This model was selected because it captures the physics of natural ventilation. Given the temperature difference of the flow (incoming and internal), there will be density differences. Therefore, some of the movement will be governed by buoyancy effects. Steady-state was selected to have an approximation on the flow behavior during an approximately uniform 10-minute period from the experiments. The measured and modelled data points show good correlation even with a coarse CFD grid (Figure 5) where the air is being modelled while the measured wall temperature data points were taken as boundary conditions.

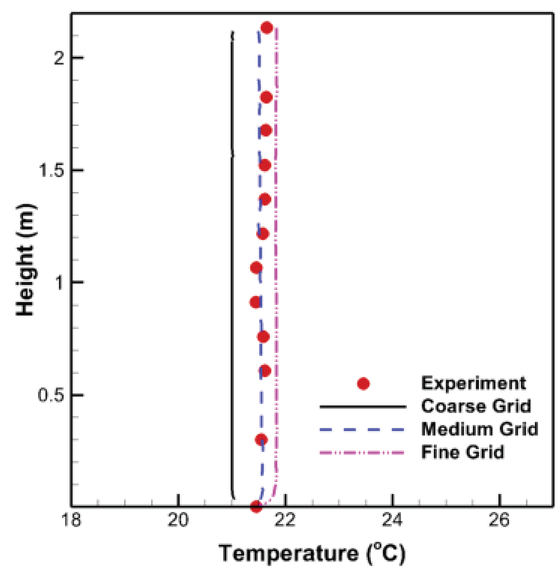

Figure 5: Correlation of measured data in the Interlock House with fine, medium and coarse CFD grid resolution.

The equations were discretized using a finite volume method and cell-centered variables. PIMPLE, a combination of SIMPLE and PISO algorithms were used to couple pressure and velocity for steady-state and transient simulations. Specifics about the solver, buoyantPimpleFoam is located in the OpenFOAM user guide [OPENFOAM 2015]. Time derivatives use a first-order Euler method while spatial derivatives are a blend of first- and second-order.

Two Cases were simulated for each building. Interlock Case 1 and Harran House Case 2 were the original measured cases, while Interlock Case 1B.1 and 1.B.2 and Harran House Case 2B were the modified cases.

Results for the Interlock House are obtained for domains of approximately 1.3 million cells. Simulations were run in 128 processors for a total of 9.1 million unknown parameters. The total gross CPU time and wall times for each case 1A are 71 and 72 hours and for case 1B are 50 and 62 hours.

For the Harran house, a transient conjugate heat transfer numerical model (that integrated CFD of the interior volume with heat transfer from/to the thick walls) was used to predict the natural ventilation flow in the Harran house using a 3D domain of the walls as well as the interior of the house. The solver, couples the temperature of the solid at the interface from the solid region to the fluid region. Results were obtained for total combined domain of solid and fluid of approximately 3 million cells. Simulations were run in 128 processors for a total of 27 million unknown parameters with total CPU time and wall time of 44 and 48 hours for case 2A; 59 and 72 hours for case 2B.

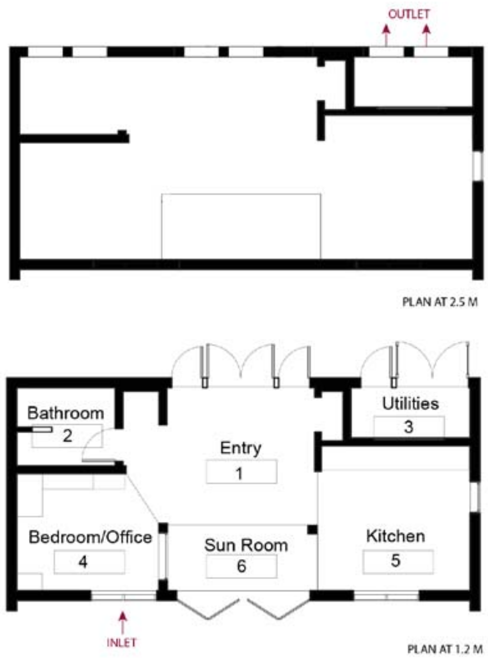

Figure 6: Interlock House floor plans indicating inlet position

6 CASE 1A: SIMULATION OF MEASURED CASE

The condition for Interlock Case 1A was modelled based on experimental measurements for a typical fall configuration with a combination of cross ventilation and stack ventilation present. One outward awning window was opened as inlet on the south facade and one clerestory outward opening awning window was opened as outlet on the north facade. Windows facing the opposite side of the wind direction can act both as inlet and outlet, because surrounding flow on the opposite side of the wind direction will be turbulent and eddies will form next to the window. In this case, the southern windward window dominantly acted as inlet, while the northern leeward window acted as outle. In this case only the interior of the house was simulated and the flow patterns were calculated based on the measured boundary conditions.

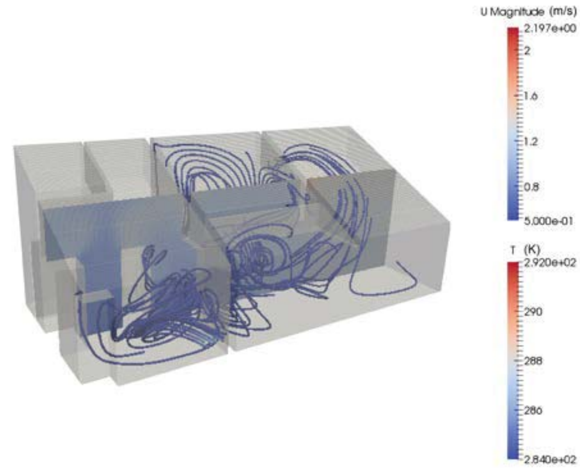

Figure 7: Interlock House Case 1A: Original case of the Interlock House as connected space with one as inlet acting window on the south façade (front) and one as outlet acting window on the north façade (back). The longitudinal plane shows temperature across the original space composition showing the lower temperature of 289 K and a moderate difference of 2^{o}K across the plane.

Inlet velocity, wind direction, and temperature in the room were used to determine a 10-minute period with the smallest variation by calculating the standard deviation of these parameters. All measurements were averaged over that given period and used in the simulations as boundary conditions for the inlet and walls. The incoming air velocity is 1.12 m/s at 45^{o} with the façade and the air temperature is 11^{o}C. The simulation of this Case Interlock 1A is visualized in Figure 6 – 8)

7 INTERLOCK HOUSE CASE 1B: SIMULATED CASES (1B.1 AND 1B.2) OF DISCONNECTED SPACES

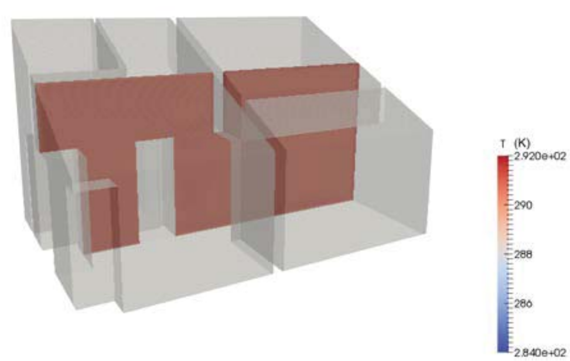

Figure 8: Interlock House Case 1B.1: Temperature slice of the detached case showing 3 to 4 degrees higher temperatures than in Figure 7

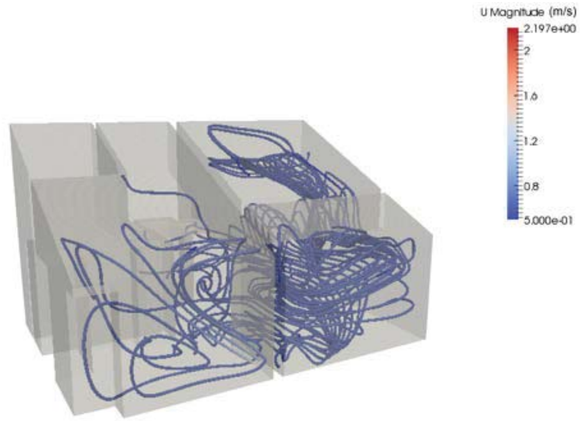

Figure 9: Interlock House Case 1B.1: Velocity streamlines are shown for the detached case.

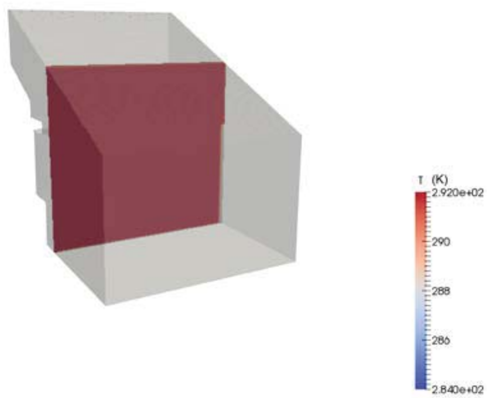

Figure 10: Interlock House Case 1B.2: Temperature gradient in the closed- off Eastern side of the building showing 4º to 5º F higher temperature than in the connected space simulation.

Then we created a model for the second case based on the Interlock House with a configuration which divided the house into two independent disconnected spaces each with one inlet and one outlet (see Figure 2). The same boundary conditions for inlet velocity and temperature were replicated in the second space, but the flow path reduced due to the different spatial configuration. Results of this fictive simulated case are visualized in Figure 8 – 11.

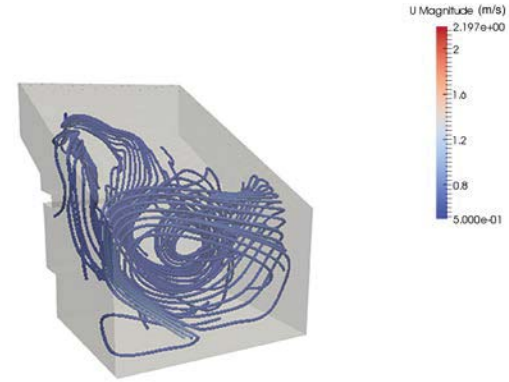

Figure 11: Interlock House Case 1B.2: velocity gradient in the closed-off Eastern side of the building.

8 HARRAN HOUSE CASE 2A: SIMULATION OF MEASURED CASE

The Harran Houses are composed of multiple interconnected square spaces each with a corbelled dome. Mutti [2014] studied two connected spaces, which create the bases for the spatial composition studied here. Their dimensions are 3m x 3.3m x 4.3 m. The domes are approximately conical in the interior with a height of 3.75 m and an approximate wall thickness of 0.63m and 0.57 m for each room. The open-faced mudbrick interior surfaces of the domes are characterized as discrete blocks to represent the mud brick better in opposition to smooth surfaces. The side of one dome is punctured by seven openings of 0.14m x 0.14m while the second dome has four opening of 0.15m x 0.17m. The top openings are circular with 0.10 m and 0.20m diameter and domes have a wall thickness of 0.22 m. Each space has a rectangular opening at person height as entrance (Figure 2 and Figure 12).

Velocity at dome openings were measured and used as boundary conditions and vary from 0.4 to 1.9 m/s. Outside measured temperature was available for March 24, 2014 at 1pm and 284.45K (11.3ºC) was used for all the opening inlets. Air temperature of door openings and openings located at the top of the domes as well as outside wall temperature of the domes and lower structure was measured and used as boundary conditions. Conductive and radiative thermal and physical properties were specified for both solid and fluid regions.

The Harran House Case 2A simulates the spatial composition as measured with the two spaces interconnected by a door opening with an additional door opening to the building exterior, located in one of the spaces. Results of this base case are visualized on Figure 13-15.

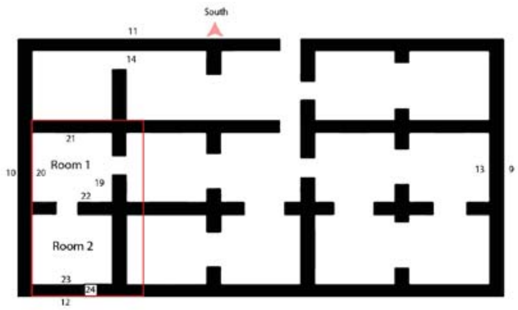

Figure 12: Harran House floor plan indicating measured rooms

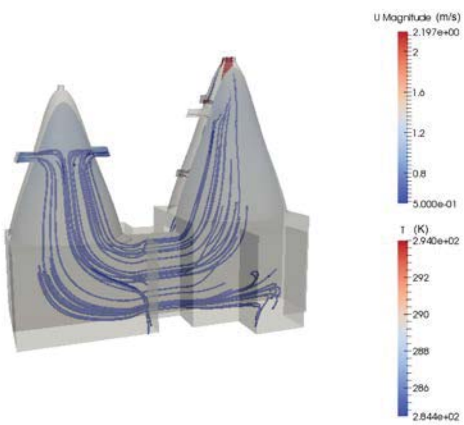

Figure 13: Harran House Case 2A: Original case with connected spaces based on measured air and wall surface temperature.

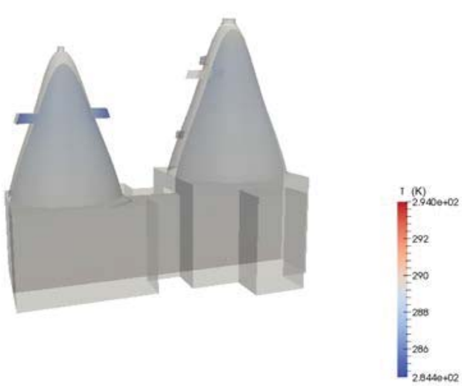

Figure 14: Harran House Case 2A: Temperature gradients for connected spaces are fairly moderate at about 2k which induces a moderate upward flow.

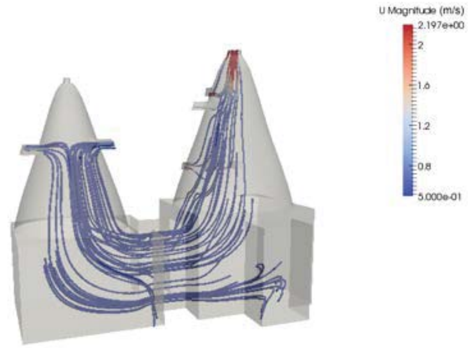

Figure 15: Harran House Case 2A: Velocity streamlines for connected spaces with high velocity of 2.2m/s only at the right outlet, while the left dome acts as inlet. The simulation also shows a cross current from the right to the left dome which slightly increases the velocity at person height

9 HARRAN HOUSE CASE 2B: CFD SIMULATION OF DISCONNECTED SPACES

The Harran House Case 2B configuration divides the house into two independent spaces by closing the large opening that interconnects the volumes, and introduces one additional door opening to the outside for each space. The punctured holes in the dome remain at the same location as in Harran Case 2A. Results for Harran Case 2B are visualized in Figures 16 – 18.

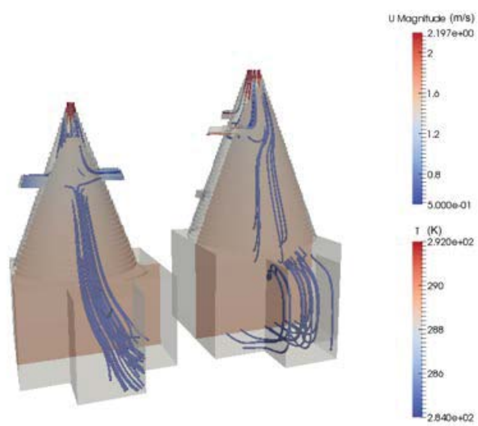

Figure 16: Harran House Case 2B: Simulated second case of the Harran house run with two separate spaces within the structure.

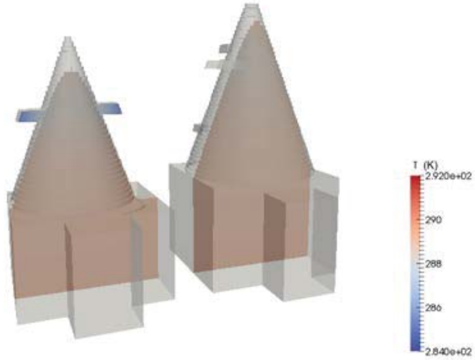

Figure 17: Harran House Case 2B: Temperature gradient for separated spaces shows a temperature difference of 6K with the higher temperature at the occupied area than in the connected case

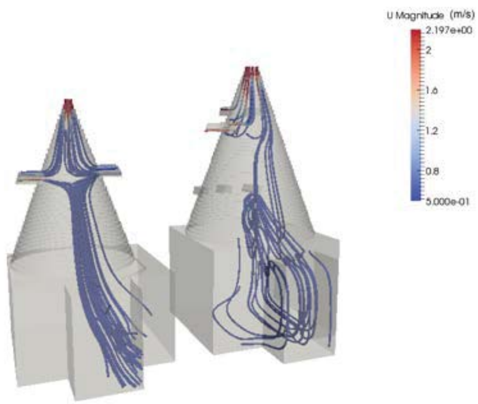

Figure 18: Harran House Case 2B: Velocity streamlines for separated spaces, which show similar velocity of 2.2m/s at the top outlet.

10 DISCUSSION AND RESULT ANALYSIS

For both buildings, natural ventilated spaces were modelled first in the original case with interconnected spaces (Interlock Case 1A and Harran Case 2A) and secondly with the respective connections closed-off (Interlock 1B.1a and 1.B.2 and Harran 2B). The original cases have been modelled and validated based upon measured data. This methodology was developed to test our hypothesis that spatial connectivity enhances the cooling and ventilation capacity of combined wind and buoyancy driven natural ventilation design scenarios. We have simulated both buildings in their original case and then simulated the spaces separately. In the Interlock House, the temperature in the single space case (Case 1B.1) shown in Figures 10, and 11, at the occupied level is about 2K to 4K higher than in the connected case (Case 1A), while air velocity remains similar in both cases. The single zone space (Case 1B.2) remains warmer and shows lower interior air velocity than the interconnected space.

In the Harran House case, a similar trend is perceived between Case 2B and Case 2A. The change in temperature and airflow performance is marginally more significant in the case of the Harran House (Case 2A Fig. 13, 14, 15). The simulation results of the two separate domes in Figures 16, 17 and 18, show that the velocity is approximately 0,5 m/s lower while the temperature is approx. 3K to 6K higher at the level of the occupant than at the occupant level of potential occupants (~1.2m above ground) in the original case 2A where the spaces were connected. Even more noticeable is a significant increase in velocity at the connecting passageway between the two domed spaces, which obviously cannot be observed in single spaces. This location of high air velocity between spaces at occupant level is important for further spatial research as it highlights the potential for cross flow with multiple dome opening configurations depending on wind directions. These increased velocities improve comfort conditions at the level of the occupant without the need for lower temperatures. While a change of 2K has only a slight impact on thermal comfort, a change in 4K or even 6K will have a significant cooling effect impact, especially with an increase of air velocity from 1 m/s to 1.5 m/s and 2 m/s at the in-/outlet (ASHRAE 55-2013).

11 CONCLUSION AND NEXT STEPS

The comparison of the two original verified CFD simulation cases, which were based on measured observations from experiments with cases where the spaces had been disconnected, provides initial indications that natural ventilation and passive strategies are directly influenced by spatial layout according to a number of factors including proportions, connectedness, and placement of inlet and outlet openings. The design of the flow path between the openings is thus as important as the opening size and placement themselves. The presented simulated and measured cases show preliminary results that connectedness of spaces can improve the effectiveness of natural ventilation strategies for free cooling. The cooling strategy in the Harran House relies also on the material properties and structural assembly of the building walls and roof as Mutti [2014] has shown. The material properties of the walls as well as the high outdoor temperatures outdoors might thus have also contributed to this effect.

As next steps we will develop a parametric model refining the proportional knowledge to develop a refined typology catalogue, which will support designers to develop more effective and validated natural ventilation strategies based on spatial proportional relations. The modelled cases provide first evidence that the interconnected spaces can be more effective for cooling and ventilation air exchange. This knowledge can have a transformative impact on building design in hot arid climates of the Middle-East, the continental humid climate of the US Midwest particularly with a changing warming climate and thus contribute transformative knowledge based on passive cooling strategies to engineering of sustainable high performance buildings through dynamic building information modelling

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REFERENCES

1. ASHRAE Standard 55 -2013. Thermal environmental conditions for human occupancy.
2. Basaran, Tahsin, Thermal Analysis of the Domed Vernacular Houses of Harran, Turkey, Indoor and Built Environment 2011 20: 543 originally published online 2 August 2011, DOI: 10.1177/1420326X11411237.
3. Deza, Mirka, Shan He, Ulrike Passe, Baskar Ganapathysubramanian. (2015) High Fidelity CFD Modeling of Natural Ventilation in a Solar House, ASME 2015 Conference Proceedings International Mechanical Engineering Congress and Exposition, Houston TX.
4. Faghih, Ahmadreza K. and Mehdi N. Bahadori, Solar radiation on domed roofs Energy and Buildings 41 (2009) 1238–1245.
5. Gomez-Munoza, Victor M. Miguel Angel Porta-Gandarab; Christopher Heard, Solar performance of hemispherical vault roofs Building and Environment 38 (2003) 1431 – 1438.
6. Mutti, Lucas, "Numerical simulation of a comprehensive 1-D building energy model and conjugate heat transfer analysis on the internal flow field at the Harran houses in southern Turkey for a brick corbelled internal surface" (2014). Graduate Theses and Dissertations. Paper 14049. http://lib.dr.iastate.edu/etd/14049.
7. Oezdeniz, Mesut B., A. Bekleyen, I. A. Goenuel, H. Goenul, H. Sariguel, T Ilter, N. Dalkilic, M. Yildirim, Vernacular Domed Houses of Harran, Turkey, Habitat Intl., Vol. 22, no. 4, pp. 477 -485, 1998.
8. OpenFOAM, 2015. Open foam User Guide. On the WWW, accessed May 14, 2015. URL http://cfd.direct/openfoam/user-guide/.
9. Passe, Ulrike, "Atmospheres of Space. The development of Alvar Aalto’s free flow section as a climate device," Architectural Research Quarterly (ARQ), Linking practice and research, volume 12 number ¾ 2008, Cambridge University Press, Cambridge, UK, 2008.
10. Passe, Ulrike. "Sustainable Building Typology: Free flow open space as climate technology." The International Journal of Environmental, Social, Cultural and Economic Sustainability, Vol. III, Issue 4. Common Ground Publisher, Melbourne (2007): 15-28.
11. Passe, Ulrike, “Evaluating passive and active solar design and performance interaction: First measured results," in Proceedings of The Second International Conference on Building Energy and Environment (COBEE), August 1-4, 2012, Boulder, Colorado, edited by Dr. Zhiqiang Zhai, Dr. Xiangli Li and Haidong Wang, 2012: 265.
12. Passe, Ulrike, “Traveling Michel Serres’ Passage du NordOuest: what happens, once the ice breaks?” ARCC, Detroit, MI, 20-24 Apr 2011.
13. Passe, Ulrike, Francine Battaglia, Designing Spaces for Natural Ventilation: An Architect’s Guide, London, New York: Routledge 2015.
14. Passe, Ulrike, Baskar Ganapathysubramanian, Bulent Yesilata. The Harran Houses as a case study for solar assisted passive ventilation and cooling. Proceedings of the Turkish Solar Energy conference SolarTR 2014 in Izmir, Turkey edited by Yesilata, B. Bayraktar K, and Kocar, G,
15. Runsheng, Tang, I.A. Meir, Y. Etzion, An analysis of absorbed radiation by domed and vaulted roofs as compared with flat roofs, Energy and Buildings 35 (2003) 539–548.
16. Stoakes, Preston, Ulrike Passe, Francine Battaglia, “Predicing natural ventilation flows in whole buildings. Part 1: The Viipuri Library”, Building Simulation, 4(3), 263-276, 2011.
17. Stoakes, Preston, Ulrike Passe, Francine Battaglia, “Predicing natural ventilation flows in whole buildings. Part 2: The Esherick House”, Building Simulation, 4(4), 365-377, 2011.